τ Lepton Mass Measurement at KEDR

Simon Eidelman
(for the KEDR Collaboration)

Budker Institute of Nuclear Physics,
Novosibirsk, Russia

Outline

1. m_τ and lepton universality
2. KEDR measurement
3. Do we need higher m_τ precision?
4. Conclusions

Test of Lepton Universality in Leptonic Decays

$$r = \left(\frac{G_\tau}{G_\mu}\right)^2 = \left(\frac{G(\tau^- \to e^- \nu_\tau \bar{\nu}_e)}{G(\mu^- \to e^- \nu_\mu \bar{\nu}_e)}\right)^2 = \left(\frac{m_\mu}{m_\tau}\right)^5 \left(\frac{t_\mu}{t_\tau}\right) \mathcal{B}(\tau^- \to e^- \nu_\tau \bar{\nu}_e) \frac{F_{cor}(m_\mu, m_e)}{F_{cor}(m_\tau, m_e)}$$

r	t_τ, fs	$\mathcal{B}(\tau^- \to e^- \nu_\tau \bar{\nu}_e)$, %	m_τ, MeV	Comments
0.9405	305.6 ± 6.0	17.93 ± 0.26	$1784.1^{+2.7}_{-3.6}$	PDG, 1992
± 0.0249	± 0.0185	± 0.0136	$^{+0.0071}_{-0.0095}$	-2.4σ
0.9999	291.0 ± 1.5	17.83 ± 0.08	$1777.0^{+0.30}_{-0.27}$	PDG, 1996
± 0.0069	± 0.0052	± 0.0045	± 0.0008	-0.01σ
1.0020	290.6 ± 1.1	17.84 ± 0.06	$1776.99^{+0.29}_{-0.26}$	PDG, 2004
± 0.0051	± 0.0038	± 0.0034	± 0.0008	$+0.4\sigma$

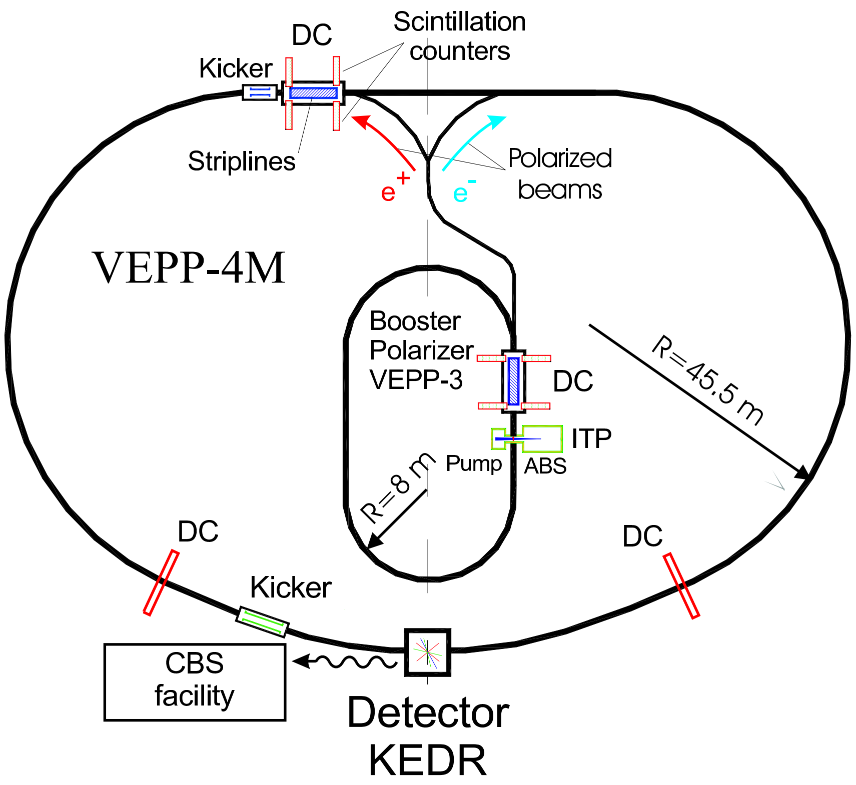
Two Methods of m_τ Measurement

- Energy dependence of $\sigma(e^+e^- \to \tau^+\tau^-)$ near threshold,
  $\sigma(e^+e^- \to \tau^+\tau^-) = 86.85\ (\text{nb})/\text{s}(\text{GeV}^2)\ \sqrt{1 - 4m_\tau^2/s}\ (1 + 2m_\tau^2/s)$
- First used by DELCO in 1978
- World-average mass dominated by BES, 1996
  that improved precision by an order of magnitude
- Pseudomass, reconstruction of the invariant mass and energy
  of the hadronic system in hadronic τ decays
- Suggested and first used by ARGUS in 1992
- Improved by a factor of ~ 5 by Belle, 2007 and BaBaR, 2008

History of m_τ Measurements

m_τ, GeV	$N_{\rm ev}$	Group	$\sqrt{s}$, GeV	Method
1783^{+3}_{-4}	692	DELCO, 1978	$3.1 - 7.4$	σ
$1776.3 \pm 2.4 \pm 1.4$	$11k$	ARGUS, 1992	$9.4 - 10.6$	P/m
$1776.96^{+0.18+0.25}_{-0.21-0.17}$	65	BES, 1996	$3.54 - 3.57$	σ
$1778.2 \pm 0.8 \pm 1.2$	$98.5k$	CLEO, 1997	10.6	P/m
$1775.1 \pm 1.6 \pm 1.0$	$13.3k$	OPAL, 2000	~ 90	P/m
$1776.99^{+0.29}_{-0.26}$	–	PDG, 2006	–	

VEPP-4M: General Layout



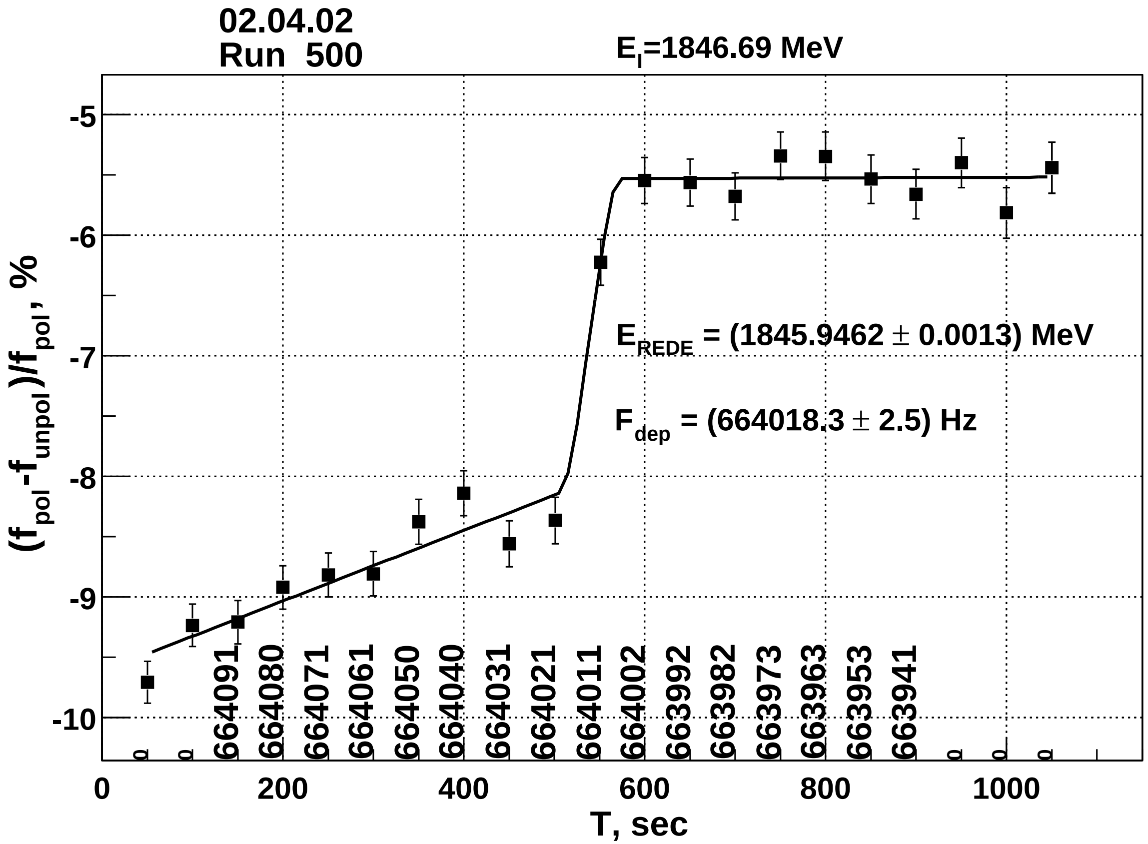
- VEPP-4M: $\sqrt{s} = 2 - 11$ GeV
- $L = 2 \cdot 10^{30}$ cm^{-2} s^{-1} at 3.6 GeV
- Physical program:
  R measurement,
  High-precision m-nt of
  D, J/ψ, ψ' masses
  Γ_{ee}, $\mathcal{B}(J/\psi \to \eta_c \gamma)$
  $\gamma\gamma$ physics

Energy Measurement at KEDR

Two methods used - resonant depolarization and Compton backscattering

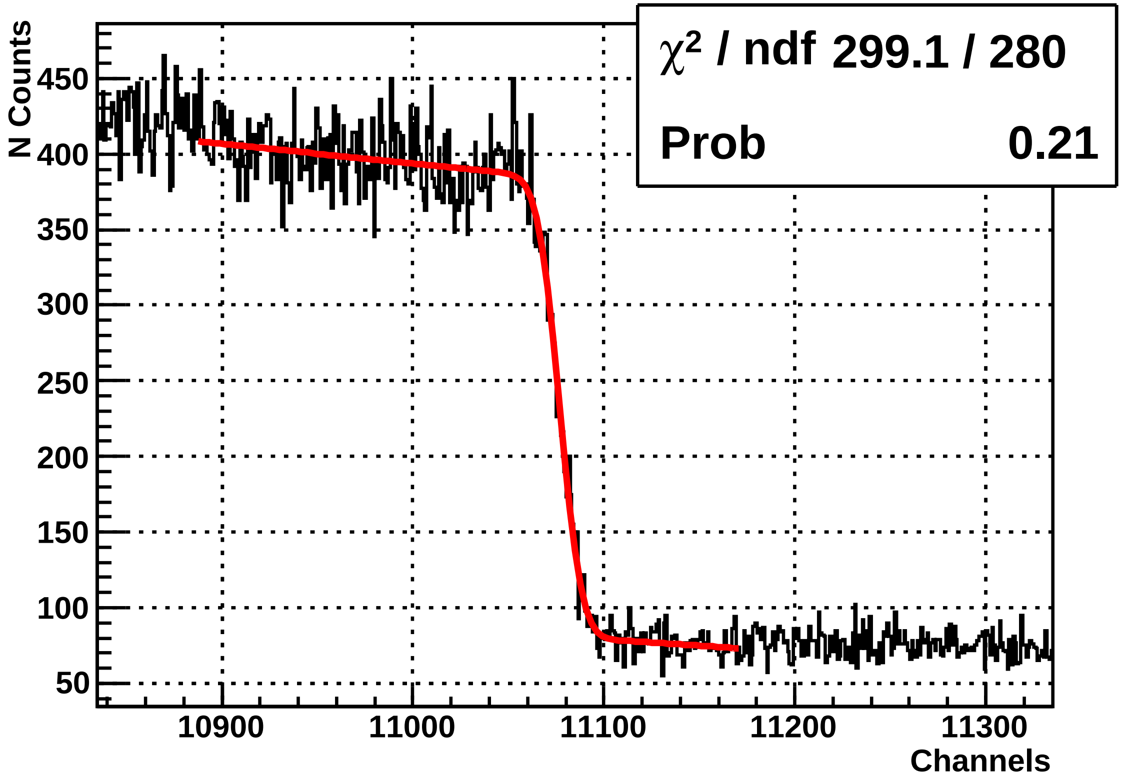
- Resonant depolarization (RD) suggested at BINP in 1975,
  $\Omega/\omega = 1 + \gamma \cdot \mu'/\mu_0$,
  Ω – spin precession frequency, ω – revolution frequency,
  $\mu'(\mu_0)$ – anomalous (normal) parts of emm
- Allows instant precision of $\sim 10^{-6}$
  with a long-term one $(0.5 - 1.7) \cdot 10^{-5}$ (8-30 keV)
- Compton backscattering (CBS) suggested at BESSY in 1997,
  energy determined from the spectrum edge,
  can be used during data taking
- Allows precision 50-70 keV at the τ threshold

Typical RD Run at VEPP-4M



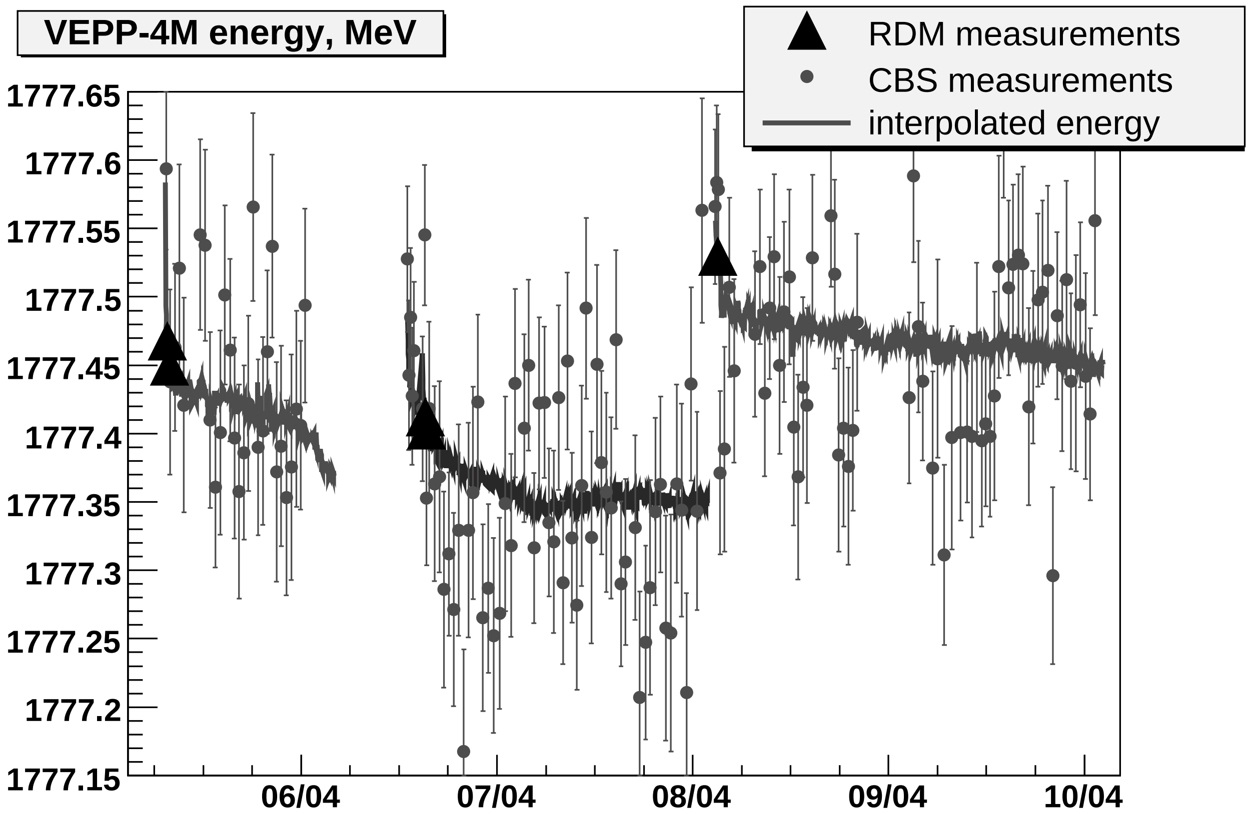
The resonant depolarization (RD) once a day with $\sigma_E < 20$ keV

Typical CBS Spectrum Edge at VEPP-4M



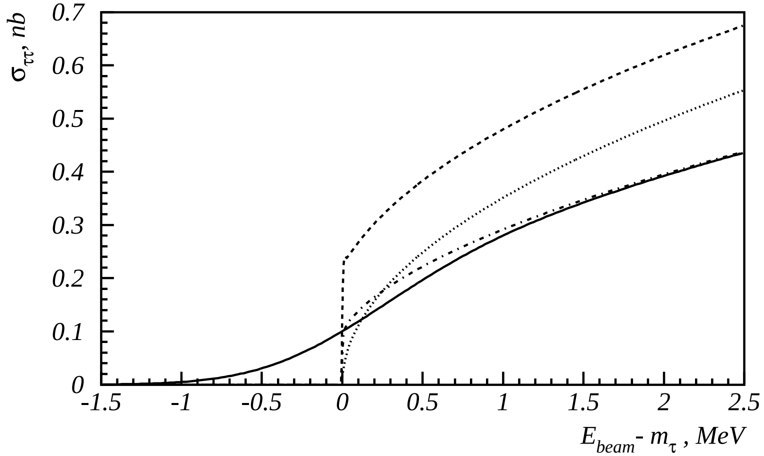
Between the RD, the Compton backscattering (CBS) with $\sigma_E < 100$ keV

VEPP-4M Energy Behaviour



During the run, E measured by CBS and from interpolation

$\sigma(e^+e^- \to \tau^+\tau^-)$ Near Threshold



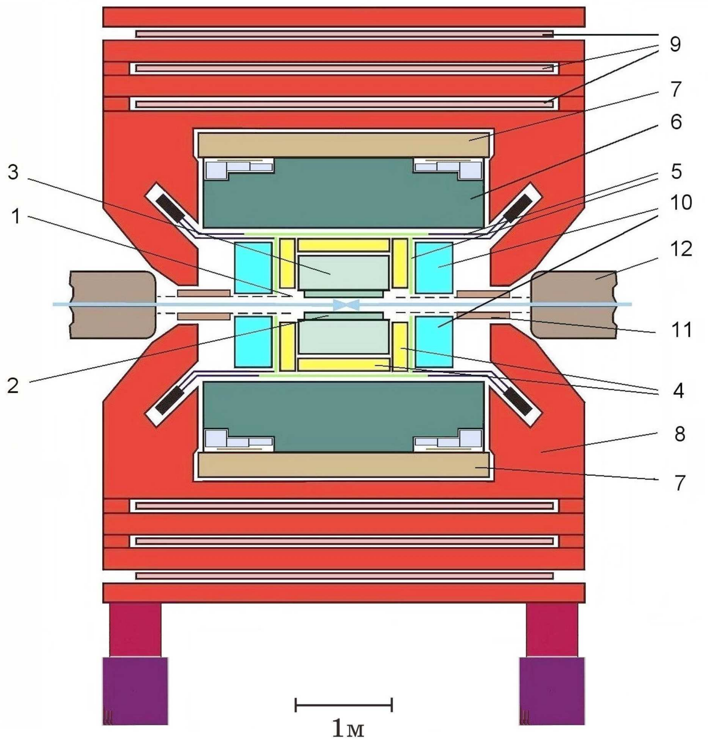
$$\sigma(W) = \frac{1}{\sqrt{2\pi}\sigma_W} \int dW' \exp\left\{-\frac{(W-W')^2}{2\sigma_W^2}\right\} \int dx\, F(x, W')\, \sigma_{fs}(W'\sqrt{1-x}),$$

$$F_c(\beta) = (\pi\alpha/\beta)/(1-\exp(-\pi\alpha/\beta)), \quad \beta = (1-(2m_\tau/W)^2)^{1/2}$$

Dotted – Born, dashed – Coulomb, FSR and VP,

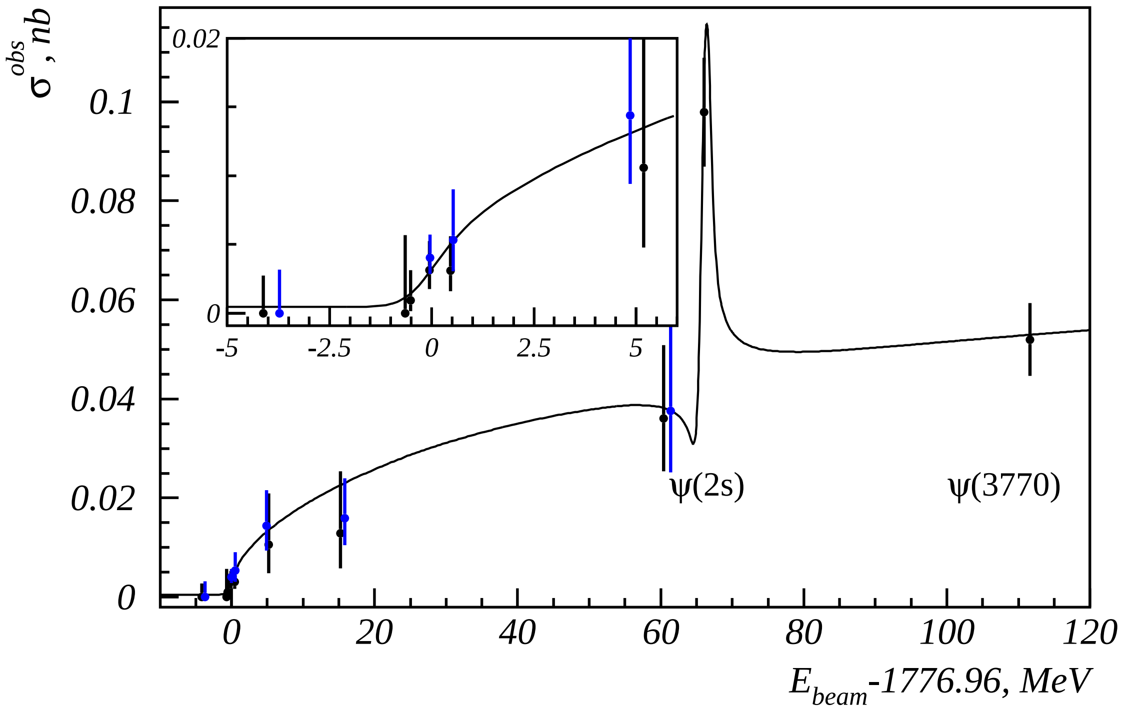
dash-dotted – ISR, solid – beam energy spead

KEDR Detector



1) Vacuum chamber, 2) Vertex detector,
3) Drift chamber, 4) Aerogel counters,
5) ToF–counters, 6) LKr calorimeter,
7) Superconducting coil, 8) Magnet yoke,
9) Muon tubes, 10) CsI calorimeter,
11) Compensation solenoid,
12) VEPP–4M quadrupole

m_τ at KEDR: Observed $\sigma(e^+e^- \to \tau^+\tau^-)$



Two big scans with 6.7 fb^{-1} in 2006 and 8.5 fb^{-1} in 2008

m_τ at KEDR: Summary of the 1st scan

Point	$< E >$, MeV	$\int Ldt$, nb^{-1}	$N_{\tau\tau}$	$\sigma^{obs}_{\tau\tau}$, pb
1	1771.945 ± 0.160	668	0	$0.0^{+2.8}_{-0.0}$
2	1776.408 ± 0.086	1382	1	$0.7^{+1.7}_{-0.6}$
3	1776.896 ± 0.045	1605	6	$3.7^{+2.2}_{-1.5}$
4	1777.419 ± 0.061	1288	4	$3.1^{+2.5}_{-1.5}$
5	1782.103 ± 0.060	283	4	$14.1^{+11.3}_{-6.8}$
6	1792.457 ± 0.102	233	3	$12.9^{+12.5}_{-7.1}$
7	1837.994 ± 0.092	305	14	$45.8^{+16.0}_{-12.2}$
8	1843.040 ± 0.065	807	79	97.9 ± 11.0
9	1888.521 ± 0.228	967	49	50.7 ± 7.2
Total	Without $\psi(2S)$	6731	81	

$$m_\tau = 1776.81^{+0.25}_{-0.23} \pm 0.15 \text{ MeV}/c^2$$

m_τ at KEDR: 2008 preliminary

Year	2006	2008
$\int Ldt$, pb^{-1}	6.7	15.2
N_{ev} at thr.	11	26
m_τ, MeV	$1776.81^{+0.25}_{-0.23} \pm 0.15$	$1776.69^{+0.17}_{-0.19} \pm 0.15$

KEDR, 2007: V.V. Anashin et al., JETP Letters 85, 347 (2007)

KEDR, 2009: A.G. Shamov et al., Nucl. Phys. B (Proc. Suppl.)189, 21 (2009)

m_τ at KEDR: Systematic Uncertainties

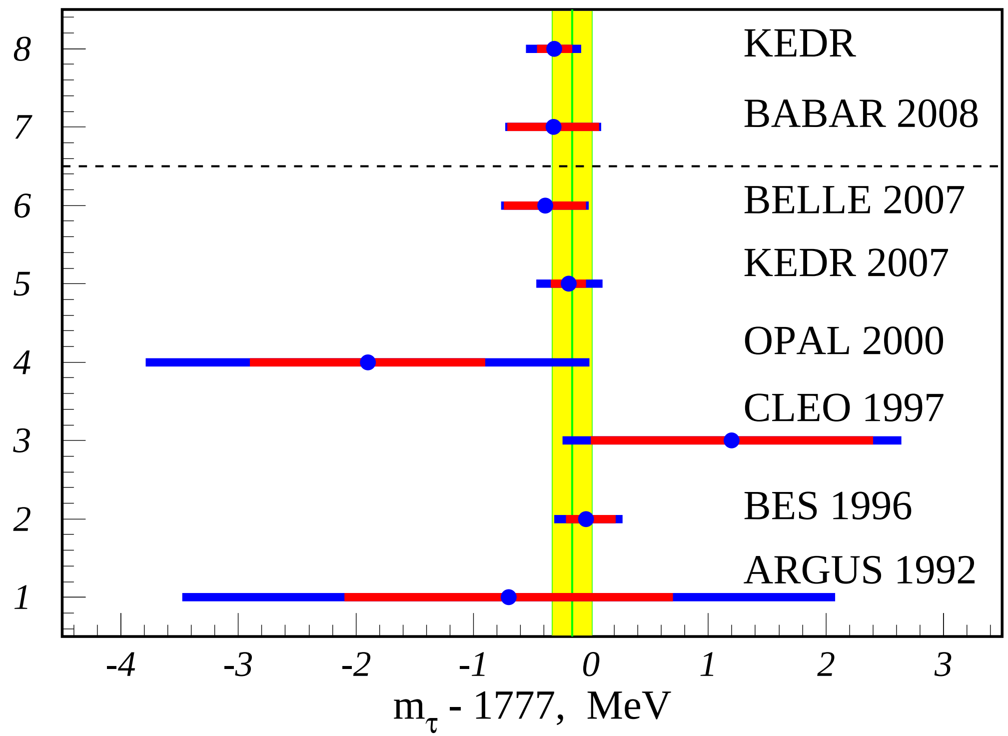
Source	σ, keV/c^2
Beam energy	35
Detection efficiency	120
Energy spread accuracy	20
BG energy dependence	20
Luminosity measurement	80
Energy spread variation	10
Cross section	30
Total	150

Work on detector-related systematics in progress

Progress of m_τ

Group	m_τ, MeV
BES, 1996	$1776.96^{+0.18+0.25}_{-0.21-0.17}$
PDG, 2006	$1776.99^{+0.29}_{-0.26}$
KEDR, 2007	$1776.81^{+0.25}_{-0.23} \pm 0.15$
Belle, 2006	$1776.61 \pm 0.13 \pm 0.35$
PDG, 2008	1776.84 ± 0.17
BaBar, 2008	$1776.68 \pm 0.12 \pm 0.41$
PDG, 2010	1776.82 ± 0.16
KEDR, 2009	$1776.69^{+0.17}_{-0.19} \pm 0.15$

Summary of M_τ Measurements



Red error bars - systematics, blue - total error

Do We Need Higher m_τ Precision?

- Masses of charged leptons are fundamental constants and should be measured with high precision

Particle	Mass, MeV	σ_m/m
e	$0.510998910 \pm 0.000000013$	$2.5 \cdot 10^{-8}$
μ	$105.6583668 \pm 0.0000038$	$3.6 \cdot 10^{-8}$
τ	1776.82 ± 0.16	$9.0 \cdot 10^{-5}$

- Tests of lepton universality involve m_l^5, effects of New Physics – m_l^2
- The QED term in $(g-2)_\mu$ is sensitive to the m_τ accuracy through the 2-loop term.
- Koide formula, 1981 (pure numerology?)

$$\frac{(\sqrt{m_e}+\sqrt{m_\mu}+\sqrt{m_\tau})^2}{(m_e+m_\mu+m_\tau)} = 1.4999973^{+0.0000395}_{-0.0000304}$$

Systematic uncertainties in M_τ

Source	BaBar	Belle
CM energy and $\|p\|$ reconstruction	0.40	0.26
MC Modeling ($\tau \to 3\pi\nu_\tau$)	0.05	0.02
MC Statistics	0.05	0.14
Fit Range	0.05	0.04
Parameterization	0.03	0.18
Momentum resolution	Negl.	0.02
Background	Negl.	0.01
Total	0.41	0.35

Belle K. Belous et al., Phys. Rev. Lett. 99, 011801 (2007)

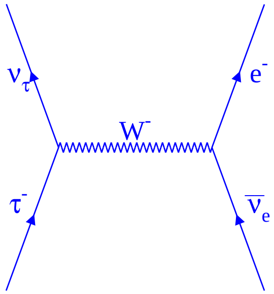
BaBar B. Aubert et al., Phys. Rev. D 80, 092005 (2009)

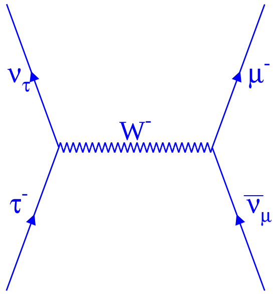
Conclusions

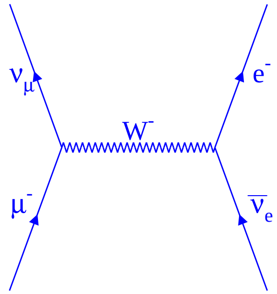
- Serious improvement of the m_τ precision at KEDR as well as at Belle and BaBar
- Results of the new measurements are in excellent agreement and confirm a lower value first obtained by BES
- New world-average value of m_τ is a factor of 2 more precise
- Precision of $|G_\tau/G_\mu|$ improved
- Further progress of $|G_\tau/G_\mu|$ impossible without improving t_τ and $\mathcal{B}(\tau^- \to e^-\nu_\tau\bar{\nu}_e)$
- Further progress in m_τ is possible at BES and probably at B factories

Backup

Leptonic Universality in Leptonic Decays – I







$$\Gamma(L \to l \nu_L \bar{\nu}_l) \;=\; \frac{G_L^2 \;\, m_L^5}{192\pi^3} F_{\rm cor}(m_L, m_l)$$

$$F_{\rm cor}(m_L, m_l) = f(m_l^2/m_L^2)\; F_{\rm W}\; F_{\rm rad}$$

$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 ln x$$

$$F_{\rm W} = 1 + \frac{3}{5}\frac{m_l^2}{m_W^2}, \qquad F_{\rm rad} = 1 + \frac{\alpha(m_L)}{2\pi}\left(\frac{25}{4} - \pi^2\right)$$

Lepton universality: $G_e = G_\mu = G_\tau = G_{\rm F}$

Lepton Universality in Leptonic Decays – II

$$r = \left(\frac{G_\tau}{G_\mu}\right)^2 = \left(\frac{G(\tau^- \to e^-\nu_\tau\bar{\nu}_e)}{G(\mu^- \to e^-\nu_\mu\bar{\nu}_e)}\right)^2 = (\frac{m_\mu}{m_\tau})^5(\frac{t_\mu}{t_\tau})\mathcal{B}(\tau \to e\nu_\tau\bar{\nu}_e)\frac{F_{\rm cor}(m_\mu, m_e)}{F_{\rm cor}(m_\tau, m_e)}$$

Correction	μ	τ
$f(m_e^2/m_L^2)$	0.9998	1.0000
$F_{\rm W}(m_L)$	1.0000	1.0003
$F_{\rm rad}(m_L)$	0.9958	0.9957
Total	0.99558	0.99597

Lepton universality $\Rightarrow r = 1$

Physics at VEPP-4M

- $\sqrt{s}$ from 2 to 11 GeV
- Originally designed for b quark physics
  is now running in the charmonium region
- $L_{\rm max} = 2 \times 10^{30}$ cm^{-2}s^{-1} at 1.78 GeV
- Properties of ψ family states, 2γ physics
- High-precision mass measurements (J/ψ, $\psi(2S)$, τ) based on
  two independent methods of energy determination:
  Resonant depolarization for absolute calibration (slow)
  Compton backscattering of laser 0.12 MeV photons (fast)

Resonant Depolarization – I

Usual NMR based absolute energy determination – $3 \cdot 10^{-4}$

Resonant depolarization suggested at BINP in 1975

gives at least an order of magnitude better precision

In a storage ring with a flat orbit:

$$\Omega/\omega_0 = 1 + \gamma \cdot \mu'/\mu_0,$$

Ω – spin precession frequency, ω_0 – revolution frequency,

μ'/μ_0 – the ratio of the anomalous (normal) parts of emm known with an accuracy of 10^{-9}

The average ω_0 is determined by the RF frequency of the guiding field and can be set and determined with high accuracy

Ω is measured at the moment of depolarization by the external electromagnetic field with a frequency ω_d:

$$\omega_\mathrm{d} \pm \Omega = k\omega_0$$

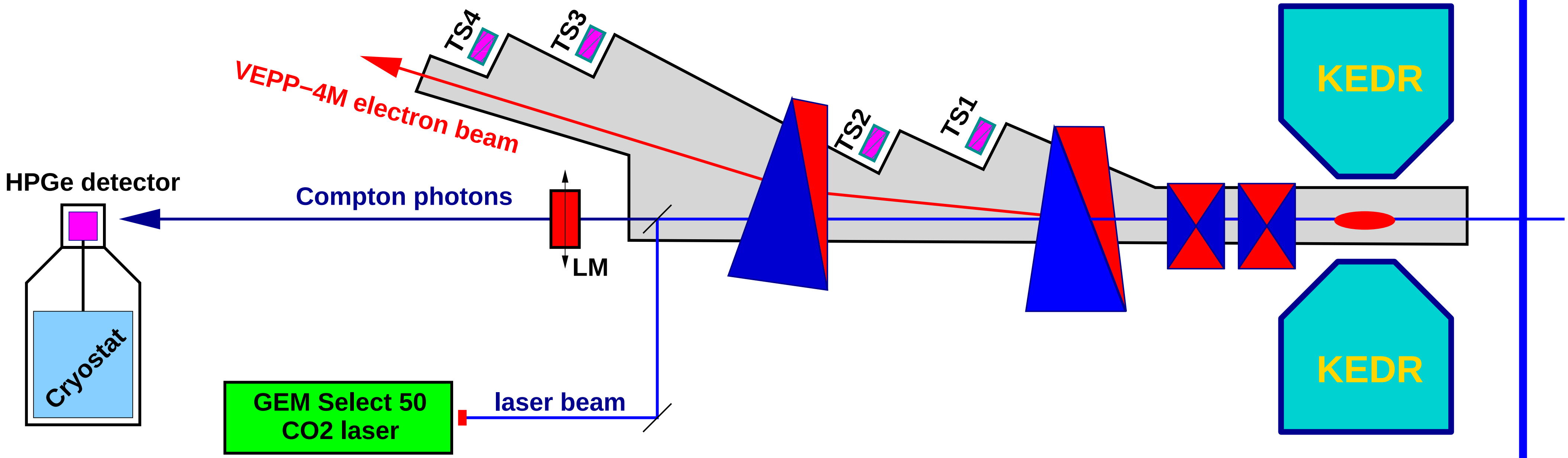
Resonant Depolarization – II

Since 1975 has been successfully used
to determine masses of various particles: $K^{\pm}$, ω, ϕ, J/ψ, $\psi(2S)$, $\Upsilon(3S)$ at BINP, $\Upsilon(1S)$ at BINP and Cornell, $\Upsilon(2S)$ at BINP and DESY, Z at CERN
Also used at various SR facilities

State	Mass, MeV/c^2	$\Delta m/m$	Factor
ϕ	1019.455 ± 0.020	$2.0 \cdot 10^{-5}$	25
J/ψ	3096.916 ± 0.011	$3.6 \cdot 10^{-6}$	90
$\Upsilon(1S)$	9460.30 ± 0.26	$2.7 \cdot 10^{-5}$	50
Z	91187.6 ± 2.1	$2.3 \cdot 10^{-5}$	60

Compton Backscattering Monitor

Realized at BESSY-I in 1987



Spectrum of CBS Photons with Calibration Lines